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The Capture of Stopped Negative Pions by Hydrogen

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Abstract. A total absorption Cerenkov γ -ray spectrometer has been used to study the relative probabilities of mesonic and radiative capture. The ratio was found to be 1.50 ± 0.15 . This result is collated with other data concerning the interaction of low-energy pions with nucleons and radiation. Reasonable consistency is found.

§ 1. INTRODUCTION

THE interaction of stopped negative pions with hydrogen was first studied in the classic experiment of Panofsky, Aamodt and Hadley (1951). They showed that two competing reactions occur:

$$\pi^- + p \rightarrow \pi^0 + n \rightarrow 2\gamma + n, \quad \dots\dots(1)$$

$$\pi^- + p \rightarrow \gamma + n. \quad \dots\dots(2)$$

The first reaction, referred to as mesonic absorption, leads to the production of a neutron of 0.40 mev energy. The two γ -rays produced by the decay of the neutral pion share between them an energy of about 138 mev. Their energy spectrum is therefore centred about 69 mev, and extends with constant intensity from a lower limit of about 55 mev to an upper limit of about 83 mev, because of the neutral pion motion before decay. In order to conserve momentum the two γ -rays are emitted in nearly opposite directions, the minimum angle between them being about 157° (Chinowsky and Steinberger 1954a).

The second reaction, radiative absorption, produces an 8.8 mev neutron and a single 129 mev γ -ray (Crowe and Phillips 1954) moving in opposite directions.

The ratio R of the probabilities of mesonic and radiative absorption was found by Panofsky *et al.* to be

$$R \equiv \frac{w(\pi^- + p \rightarrow \pi^0 + n)}{w(\pi^- + p \rightarrow \gamma + n)} = 0.94 \pm 0.30 \quad \dots\dots(3)$$

where, as in the rest of this paper, the uncertainty quoted is a standard deviation. The ratio R is referred to as the Panofsky ratio.

Since the absorption takes place when the pion is in the K shell, the reaction (1) can be related to the s-wave charge exchange scattering of low-energy negative pions. Similarly, reaction (2) can be related to the s-wave radiative capture, and so to the inverse reaction, which is the s-wave part of a photo-production process. The Panofsky ratio can in fact be calculated from the results of scattering and photo-production experiments, but until recently the value so obtained was about twice the experimental value (3).

In view of the obvious need for further data, two experiments on the high-energy γ -rays have been done at Liverpool. Both make use of the external strong-focused 96 mev negative pion beam.

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Kuehner, Merrison and Tornabene (to be published) have been using a conventional magnetic pair spectrometer of high resolution but low counting efficiency, while the experiment described here was done with a new type of Cerenkov γ -ray spectrometer, originally suggested by Kantz and Hofstadter (1954). The γ -rays are made to dissipate their energy in a cascade shower inside a block of lead glass. If the shower is fairly complete, the total length of electron track is nearly proportional to the incident electromagnetic energy. Almost all the track is relativistic so that the total amount of Cerenkov light emitted is also nearly proportional to the incident energy. Pulse-height analysis of the output from a large photomultiplier viewing the glass then gives the spectrum directly. The instrument has the advantage of high counting efficiency and, in principle, freedom from systematic errors, since the whole spectrum is observed at once in a very straightforward way. However, as will be seen, these advantages have here been only partially realized, because the resolution of the spectrometer was not quite good enough to resolve completely the two groups of γ -rays. Calibration experiments were therefore necessary in order to arrive at the separate line shapes.

§ 2. THE SPECTROMETER

The spectrometer consisted of two right cylinders of Chance EDF 653335 glass, each 5 in. in diameter and 4 in. long. These were placed in optical contact, to make a cylinder 8 in. in total length. All surfaces were polished, and a 5 in. E.M.I. photomultiplier with a photocathode sensitivity of $37 \mu\text{A}/\text{lumen}$ was placed in optical contact with one end. The γ -rays produced electron pairs in a 2 in. diameter external lead converter, and these pairs were counted by a coincidence counter and put in at the other end. This arrangement ensured that the showers in the glass started near the axis. A coaxial white shield surrounded the glass, and the radiation entered through a thin polished aluminium cap. The multiplier was shielded magnetically by coaxial soft-iron and mumetal shields.

The glass had a density of 3.9 g cm^{-3} , a refractive index of 1.69, a radiation length of 2.56 cm, and a critical energy of 16 MeV. The transmission of light of various wavelengths through ten radiation lengths of glass is shown in figure 1, together with the relative quantum efficiencies of the photocathode at the same

Figure 1. The Cerenkov spectrum, the quantum efficiency of the photomultiplier, and the transmission of the glass through 10 radiation lengths, as functions of photon wavelength.

The correspondence is reasonably good in view of the fact that the analysis has ignored several uncertain theoretical points. It is likely that various Coulomb effects have affected the positive energy data by perhaps 5 or 10% and a correction of the same order will probably appear when the calculation of T is considered more closely. Finally, Noyes (1956) has pointed out that deviations from charge independence in the pion-nucleon system have the effect of depressing the value of $w(\pi^- + p \rightarrow \pi^0 + n)$ as calculated from the scattering data. Noyes proposed a correction of 10% in this sense, but in fact the appropriate correction should probably be much smaller. The effect of the radiative transition is obviously reduced now that the value of R has been raised. It also seems likely that the range of the pion-nucleon s-interaction is much smaller than was thought at the time of the original calculation, and this too has the effect of reducing the correction required.

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Figure 7. Phenomenological scheme of connections between π^- capture processes, pion-proton scattering, photo-production, and production in nucleon-nucleon collisions.

Table 2. Capture Rates from the K Shell, calculated from Positive Energy Data

Capture Process	Transition Rate $10^{-14}w$ (sec $^{-1}$)	Input Data	Ref.
$\pi^- + p \rightarrow \pi^0 + n$	7.18 ± 1.08	(a) $\alpha_1 - \alpha_3 = (0.27 \pm 0.02)\eta$ (b) $v_0/c = 0.204 \pm 0.005$	O K <i>et al.</i>
$\pi^- + p \rightarrow \gamma + n$	4.05 ± 0.33	(c) $\sigma_s(\gamma + p \rightarrow \pi^+ + n) = (1.43 \pm 0.06)\eta \times 10^{-28} \text{ cm}^2$ (d) $r_0 = 1.87 \pm 0.13$	B <i>et al.</i> B <i>et al.</i>
$\pi^- + d \rightarrow 2n$	6.64 ± 0.72	(e) $\sigma_s(p + p \rightarrow \pi^+ + d) = (1.38 \pm 0.15)\eta \times 10^{-28} \text{ cm}^2$	C & S

In the third column α_1, α_3 are the phase shifts for s-wave pion-nucleon scattering in the $T = \frac{1}{2}, \frac{3}{2}$ states respectively; v_0 is the velocity of emission of the neutral pion in the capture process. O, Orear (1956); K *et al.*, Kuehner *et al.* (private communication); B *et al.*, Beneventano *et al.* (1956); C & S, Crawford and Stevenson (1955).

Table 3. Ratios of Transition Rates, calculated from Positive Energy Data and from Capture Data

Ratio	From positive energy data	From capture data	Difference (%)
$\frac{w(\pi^- + p \rightarrow \pi^0 + n)}{w(\pi^- + p \rightarrow \gamma + n)}$	1.77 ± 0.30	$R = 1.52 \pm 0.11$	15 ± 19
$\frac{w(\pi^- + d \rightarrow 2n)}{w(\pi^- + p \rightarrow \gamma + n)}$	1.64 ± 0.22	$ST = 1.88 \pm 0.25$	-14 ± 19
$\frac{w(\pi^- + d \rightarrow 2n)}{w(\pi^- + p \rightarrow \pi^0 + n)}$	0.92 ± 0.17	$ST/R = 1.24 \pm 0.19$	-30 ± 24

The difference column is obtained by subtracting the second value from the first and dividing by the mean.

Table 1. Branching Ratios in the Capture of Stopped Negative Pions by Hydrogen (*R*) and Deuterium (*S*)

Reference	<i>R</i>
Panofsky <i>et al.</i> (1951)	0.94 ± 0.30
Kuehner <i>et al.</i> (private communication)	1.60 ± 0.17
This paper	1.50 ± 0.15
Weighted Mean	1.52 ± 0.11
<hr/>	
	<i>S</i>
Panofsky <i>et al.</i> (1951)	2.36 ± 0.74
Chinowsky and Steinberger (1954 b)	1.5 ± 0.8
Kuehner <i>et al.</i> (private communication)	2.36 ± 0.36
Weighted Mean	2.31 ± 0.31

The uncertainties quoted are standard deviations.

(Anderson and Fermi 1952). The link is obtained in an elementary way by taking the transition rate for any one of these low-energy pion absorption processes to be proportional to the square of the modulus of the pion wave function at the position of the proton. It then follows that, apart from Coulomb effects, the absorption cross sections at very low positive energies must obey the '1/*v* law', $\sigma = A/\eta$, where $\eta = p/\mu c$ is the pion momentum *p* divided by the charged pion rest mass μ and the velocity of light *c*. The constant *A* is connected with the K-shell absorption rate *w* by the relation

$$w = cA/\pi a^3. \quad \dots\dots(5)$$

In this equation the Bohr radius *a* (*a_H* for hydrogen, *a_D* for deuterium) is calculated from the appropriate reduced pion mass.

With the help of the deuterium data the cross sections for scattering and photo-production may be linked with the s-wave cross section for a third important process, pion production in nucleon-nucleon collisions (Brueckner, Serber and Watson 1951). For this it is necessary to know the ratio

$$T = \frac{w(\pi^- + d \rightarrow 2n + \gamma)}{w(\pi^- + p \rightarrow n + \gamma)} = \frac{2}{3} \left(\frac{a_H}{a_D} \right)^3 \quad \dots\dots(6)$$

where the value given is that estimated by Brueckner *et al.* using the impulse approximation.

The complete phenomenological scheme is set out in figure 7. The processes which have actually been observed are printed in bold type, and all but one of the connecting links use either equation (5) or (6), or charge independence (c.i.) or detailed balancing (d.b.). In photo-production the ratio of the numbers of negative to positive pions produced in deuterium near threshold is taken to be equal to the ratio of the photo-production cross sections of neutrons and protons separately:

$$r_0 = \frac{\sigma_s(\gamma + n \rightarrow p + \pi^-)}{\sigma_s(\gamma + p \rightarrow n + \pi^+)} = \frac{\sigma_s(\gamma + d \rightarrow 2p + \pi^-)}{\sigma_s(\gamma + d \rightarrow 2n + \pi^+)}. \quad \dots\dots(7)$$

Table 2 shows the absolute capture rates from the K shell as predicted from the positive energy data. The corresponding mean lifetimes are all of the order of 10^{-15} second. In table 3 the rates are taken in pairs and their ratios compared with the capture data set out in table 1 and equation (6).

two small pulses may credibly be attributed to break-through of mesonic absorption events in which a low-energy Compton electron was produced in counter 6. The distribution of the remainder is reasonably consistent with the computed line shape.

The Panofsky ratio is obtained almost directly from the ratios of the areas under the low- and high-energy peaks in figures 6(a) and 6(b). Small corrections have to be applied for the energy dependence of the efficiency of the lead converters. The cross sections for pair production in lead were taken from Davies, Bethe and Maximon (1954), and a minor contribution from Compton scattering was also considered. An additional very small correction (2%) was made for the possibility that both electrons produced by a low-energy γ -ray in the $\frac{1}{8}$ in. converter might stop before reaching counter 2. This was calculated by the method of Wilson (1951).

The results, with their statistical standard deviations, are:

$$R = \begin{cases} 1.48 \pm 0.15 & (\frac{1}{8} \text{ in. converter}) \\ 1.52 \pm 0.18 & (\frac{1}{16} \text{ in. converter}) \\ 1.50 \pm 0.11 & (\text{combined result}). \end{cases}$$

An attempt was also made to review the possibilities of systematic error. It was not possible, for example, to include all physical effects in the computation of the theoretical line shapes. Some of the electrons produced in the lead converters could be severely scattered before entering the glass, and tests with the calibrating positron beam showed appreciable distortions of the pulse spectra given by electrons entering at angles greater than 45° to the normal. Reassurance about the size of errors of this kind is, however, provided by the good agreement of the results taken with $\frac{1}{8}$ in. and $\frac{1}{16}$ in. converters, and by the gated spectra shown in figures 6(c) and 6(d).

Another kind of error would arise if the background were affected by presence or absence of liquid hydrogen in the target. The distribution of the pions in the foamed polystyrene *behind* the liquid-hydrogen container will indeed be slightly affected by the stopping power and scattering of the hydrogen. In fact, however, the range of the pions in the strong-focused beam was not well defined, so that the thickness of the hydrogen and the foamed polystyrene target walls was small compared with the range straggling. A small upper limit on the background variation can be set by suitable scaling of the background given by the solid polyethylene absorber immediately *in front of* the hydrogen container.

It seemed reasonable, after reviewing these possibilities, to allow an additional standard deviation equal to the statistical one. The final result is then $R = 1.50 \pm 0.15$.

§ 4. DISCUSSION

Table 1 shows that the results of the two Liverpool experiments, which are in good agreement, raise the weighted mean value of R by about 50%. The table also shows the available data on the absorption of negative pions from the K shell of deuterium, the branching ratio S being defined by

$$S = \frac{w(\pi^- + d \rightarrow 2n)}{w(\pi^- + d \rightarrow 2n + \gamma)}. \quad \dots\dots(4)$$

As already mentioned, the ratio R can be used to link the positive energy s-wave cross sections for pion-proton scattering and pion photo-production

hydrogen, or the converter E, or both. In figure 6(c) the results, with the background subtracted, are compared with the computed pulse spectrum for the lower energy group of γ -rays. The agreement is satisfactory.

Figure 6. Pulse spectra given by the Panofsky radiation : (a) ungated, $\frac{1}{8}$ in. Pb converter ; (b) ungated, $\frac{1}{16}$ in. Pb converter ; (c) gated by γ - γ coincidences ; (d) gated by γ -n coincidences.

In the second subsidiary experiment (figure 5(c)) the additional counters 6, 7 were used to discriminate in favour of radiative absorption. The electronic gate now opened only when an event of the type $123\bar{4}6\bar{7}$ occurred. Counter 6 had a cylindrical plastic scintillator 2 in. in diameter and 2 in. long; it was able to detect, by means of proton recoils, the 8.8 mev neutrons from radiative absorption but not the 0.4 mev neutrons from mesonic absorption. Unfortunately, this counter could also detect high-energy γ -rays, through pair production or Compton scattering in the plastic scintillator. The intrinsic efficiency for counting in this way was about half the efficiency for counting 8.8 mev neutrons. However, a γ -ray interaction in counter 6 usually produced high-energy electrons which were detected in the 5 in. diameter anti-coincidence counter 7, thus cancelling the event. There was a further geometrical factor, of about three, in favour of radiative absorption. The angle between the two γ -rays produced in mesonic absorption is usually near to the minimum 157° . If one γ -ray was detected in the spectrometer, the other could miss counter 6 altogether.

The counting rate was found to be extremely low, and in fact only 32 events were collected. There was no detectable background effect with the hydrogen removed. Figure 6(d) shows the pulse spectrum in histogram form, together with the computed pulse spectrum for the high-energy group of γ -rays. The

were counted by the scintillation counter 2 and the glass counter 3 in coincidence, and the anti-coincidence counter 4 eliminated the effects of charged particles scattered from the target area. A coincidence-anti-coincidence event of the type 1234 opened the electronic gate, which allowed a linear pulse from the glass counter to pass through to the pulse analyser. The counts in counter 1 were used for monitoring.

Figure 5. The experimental arrangements used for studying the Panofsky radiation: (a) ungated, (b) gated by γ - γ coincidences, (c) gated by γ -n coincidences.

Figures 6(a) and 6(b) show the pulse spectra obtained with lead converters $\frac{1}{8}$ in. and $\frac{1}{16}$ in. thick respectively. In each case a background equal to about one third of the total effect has been subtracted. The backgrounds were caused by γ -rays which either originated elsewhere than in the liquid hydrogen or produced pairs elsewhere than in the lead converter. The effects of these were found by running with either the hydrogen or the converter, or both, removed.

The curves shown were fitted to the experimental points by taking the computed pulse spectra for the two groups of γ -rays and adding them together in proportions determined by the method of least squares.

The computed line shapes were checked directly by means of two subsidiary experiments. For the first experiment (figure 5(b)) a coincidence counter 5 and a $\frac{1}{4}$ in. thick lead converter E, both 5 in. in diameter, were introduced, and an event of the type 12345 was required to open the electronic gate. Such events were produced by mesonic absorption, when one of the two γ -rays was detected by the spectrometer and the other by counter 5. A background equal to about one quarter of the total effect was found after removing either the

that the beam was passed through a lead converter 6.3 mm thick and the field of the analysing magnet was reversed. The negative pion beam was contaminated in the usual way by 190 mev negatrons, which started showers in the lead and so produced positrons. Beams of these positrons, with various energies, were selected by the analysing magnet and directed on to the counters. The pions and muons present, being negative, were deflected out of the way by the magnet.

The glass counter, without the lead converter, was put in coincidence with the normal collimating counter and with another scintillation counter defining the line of flight of the positrons. When a triple coincidence occurred an electronic gate opened, and a proportional pulse from the glass counter was sent to a 50-channel pulse analyser. The spectra observed with positrons of various energies are given in figure 3, where the fitted curves are gaussian distributions. The shapes of these spectra, and the ratios of triple coincidences to double coincidences between the two scintillation counters alone, show that the counting efficiency of the glass is 100% in this energy range. Figure 4 shows that the voltage output of the counter is proportional to the positron energy, and that the line widths are nearly proportional to the square root of the energy. In these circumstances the response of the counter to a pair of electrons of a given total energy is essentially the same as the response to a single electron of that energy.

Figure 4. Mean pulse heights, and line widths, of the spectra shown in figure 3.

The positron data were then used to compute the line shapes produced in the complete spectrometer by the γ -rays from mesonic and radiative absorption. The small effects of energy losses by ionization in the converter and collimating counter were taken into account, but bremsstrahlung losses were ignored because the corresponding radiation passed into the glass and made its contribution to the shower.

§ 3. EXPERIMENTAL PROCEDURE AND RESULTS

The apparatus used for studying the complete spectrum of the γ -radiation is shown in figure 5(a). The negative pions were slowed down in polyethylene absorbers A and B, passing through the scintillation counter 1 on the way. Some of the pions stopped in the liquid hydrogen target C, which was made from foamed polystyrene. The active volume of the target was a cylinder $1\frac{1}{2}$ in. in diameter and $1\frac{1}{2}$ in. high. As already mentioned, the γ -radiation was observed through the production of electron pairs in a lead converter D. The electrons

wavelengths. There are some wavelengths at which both figures are reasonably large but the short wavelength cut-off in the transmission is clearly a limitation, especially since the number of quanta per unit wavelength interval in the Cerenkov radiation is proportional to λ^{-2} . The type of glass used in the spectrometer offered the best transmission per radiation length at short wavelengths.

The arrangement used for calibrating the spectrometer is shown in figure 2. The layout was the normal one for work with 96 Mev negative pions, except

Figure 2. The experimental arrangement used to obtain positrons for calibrating the spectrometer.

Figure 3. The response of the spectrometer to positrons with various energies in the range 32-125 Mev.